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MEASUREMENT TECHNOLOGY FOR AUTOMATION IN CONSTRUCTION AND LARGE SCALE ASSEMBLY

Proceedings of a workshop sponsored by National Bureau of Standards & Transitions Research Corporation Feb. 5-6, 1985

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MEASUREMENT TECHNOLOGY FOR AUTOMATION IN CONSTRUCTION AND LARGE SCALE ASSEMBLY

Proceedings of a Workshop

Editor: John M. Evans

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Manufacturing Engineering
Robot Systems Division
Metrology Building, Room B124
Gaithersburg, MD 20899

August 1985

U.S. DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary
NATIONAL BUREAU OF STANDARDS
Ernest Ambler, Director

EXECUTIVE SUMMARY

Fifty technical experts from business, industry, universities and government met in Washington, D.C., on February 5 and 6, 1985, to consider the issues of applying automation to construction and large scale assembly. This workshop, which was sponsored by the National Bureau of Standards and Transitions Research Corporation, concluded that:

o New technology achievable in the near term would have a major benefit in the construction and large scale assembly industries.

o The key to this benefit is the application of computers to data management and process control both off-site for design and planning and on-site for inventory management, production control and creation of an as-built data base.

o The achievement of this new technology requires research carried out on the integration of systems for measurement and automated control of on-site construction and assembly tasks.

Representatives of construction firms, heavy equipment manufacturers, shipbuilders, and related industries identified four key technical barriers to the introduction of automated manufacturing technology to the building and assembly sites. The priority order for technology development was:

1. The need for computerized data bases, particularly a demonstration of an as-built data system including standardized data elements and interfaces.

2. The need for automated systems for inventory management, particularly on-site part labeling and tracking of materials handling equipment.

3. The need for on-site metrology, specifically to measure the characteristics of the construction as actually built to feed an as-built data base with important data on position, dimensions, and quality control.

4. The need for real-time measurements for automatic machine control, particularly for semi-automatic machines for which the process control is automatic with the operator driving the machine and controlling the set points. Lifting (cranes) and materials handling are the most important.

Based on the Delphi technique, the group of experts estimated the relative economic importance to industry of various technologies in the near future:

- o Judged to be most important over the next ten years:
  - Computer Aided Design (CAD) systems
  - Computerized inventory control and material scheduling
  - Computer assisted surveying and measurement
- o Judged to be very important:
  - Semi-automated control of machinery for ditching grading, lifting, positioning, and material handling
  - Computer control of cut-off equipment for boards, panels and masonry
  - Computer control of spraying equipment for painting, fireproofing, plaster, concrete, etc.

Also based on the Delphi technique, the experts predicted the year when various technologies would achieve degrees of penetration of the marketplace. For example:

- o The next five years will see
  - 5% of new construction equipment having semi-automatic control, such as laser level control of grader blades
  - 5% of shipyards and aircraft plants using position sensing systems for navigation and control of materials handling equipment
- o The next ten years will see
  - 50% of new construction equipment with semi-automatic control
  - 5% of construction digging, grading and ditching done with equipment controlled from a computer database
  - 5% of commercial construction will have automatic position sensing systems for navigation and control of equipment and as-built data bases for on-site part fabrication

According to the consensus of the attendees at the workshop after the two days of discussions, the specific problems that need attacking are:

1. System integration and standardization of data base technology for on-site use, for integration with measurement and inventory management systems, and integration with off-site computers.

2. Standardization of labeling for inventory management.

3. Development of real-time measurement technology for measuring position and dimensions and for inspection for quality assurance, particularly in materials properties (e.g. concrete).

4. Development of better machine control technology, particularly for lifting (cranes) and for material handling.

Specific recommendations for action included:

- o Information transfer: a source of information on measurement technology that could be applied in construction and a major conference on this topic next year.

- o A demonstration project to develop and demonstrate an as-built data base on a real construction project.

MEASUREMENT TECHNOLOGY FOR AUTOMATION IN CONSTRUCTION AND LARGE SCALE ASSEMBLY

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SECTION I: INTRODUCTION

The potential impact of automation in construction is enormous. Recent developments in industrial automation in the relatively constrained environment of the factory have progressed to the point where it is possible to consider applications of automation technology to the more complex and unconstrained environment of the construction site.

The use of computers in computer aided design, purchasing, and project management is well established. The use of computers on the construction site is very limited at this point in time and offers great potential for improved management, material control, and control of construction equipment. Some machines already used on construction projects have sensors and processing ability that bring them near the realm of robotics: automated paving machines, tunnel boring machines, automated forklifts, and ditching and grading machines guided by lasers with computerized controls.

In Japan, construction robots are starting to be used for tasks such as spraying fireproofing on structural steel, lifting and positioning steel beams, and finishing concrete. In the U. S., several university research groups are working on automation in construction, and the Department of Defense is developing autonomous and semi-automatic systems for reconnaissance and logistics support that researchers have pointed out would be applicable to construction tasks.

In the future, a variety of new construction technologies and automated and semi-automated construction equipment can be envisioned:

* On-site computers, computer databases, and measurement instruments and machines with computer interfaces.

* Automatic tracking of materials handling equipment for improved inventory control.

* Equipment driven from computer databases which can automatically cut materials (such as pipes, pipe hangers, ducts, boards, panels, tile, etc.) to size or to fit.

* Portable computer-controlled machines which can lay floors, ceilings, roofs; or can install walls, windows, doors, etc.

* Heavy lifting and positioning devices such as cranes, high-lift forks, or cherry pickers which can be fitted with sensors and used for transporting and automatically positioning heavy materials such as steel plates, concrete wall panels, floor supports, vertical columns, etc.

There are major technical barriers that must be overcome before this potential can be realized. One of these is the lack of computerized databases that can store and retrieve both as-designed and as-measured information for construction projects. A second is the lack of measurement technology that can conveniently and rapidly make accurate position measurements over large cluttered volumes under variable climatic conditions.

Two types of measurement problems are encountered: measurements of position and dimension to feed an as-built data base for use in on-site fabrication and life cycle maintenance, and real time measurements used for closing a control loop for process control or equipment navigation.

Measurement techniques which could establish a metric over the entire volume of the building site could be used for materials transport, part positioning, and structural inspection and would enable design information to be compared with actual construction results. They would enable automatic or semi-automatic control of ditching, grading, and excavation equipment for site preparation. They would allow building materials to be transported, stored, retrieved, and delivered "just in time" and cut to size for assembling and fastening with the required tolerances. They would allow lifting and positioning machinery to place beams, panels, plates, and pipes in accordance with the design specifications as modified by as-built measurements.

In order to assess these problems and determine their importance to industry, the National Bureau of Standards and Transitions Research Corporation collaborated to organize a Workshop to identify and prioritize research topics.

Many of these same measurement and control problems are encountered in shipbuilding and aircraft assembly. As a result, the scope of the workshop was broadened to include both construction and large scale assembly.

The workshop drew together a group of experts from industry, government, and academia to discuss the current state of the art in automation for construction and large scale assembly and to determine needs and priorities for future research.

The attendance list is included in Appendix A. The initial target attendance was 25-35, the final attendance was 50, indicating the interest in this area.

Objectives:

Specific objectives were:

1. To assess the current use of automation in construction and large scale assembly and to forecast additional uses in the future.

2. To determine measurement technology requirements that must be met for successful application of automation to construction and large scale assembly.

3. To determine needs and priorities for future research.

Format:

The format of the workshop was oriented toward small group discussions to allow a maximum of input from the participants. The agenda follows.

Section II contains abstracts of the prepared presentations.

The results of the small group discussions are reviewed in Section III. Discussion was subsequently organized into four topical areas: on-site metrology, machine control, data bases, and inventory control. These topics came up in each of the groups. The summary of the discussions of each of these topics is presented in Section IV.

As a part of the workshop, a Delphi Forecast was conducted on the development, implementation, and economic impact of the technologies discussed. The results of the final round of the Forecast are presented in Section V.

Section VI offers a summary and conclusions from the Workshop.

It is hoped that these proceedings will be useful both to the participants and to a broader audience in stimulating thought and guiding research efforts in the development and application of automation in construction and large scale assembly.

AGENDA

DAY 1, MORNING

8:30 am	Introduction and Workshop Objectives Collection of First Round Delphi Forecast Inputs
8:45 am	Session One: Prepared Presentations

1) Measurement Technology Requirements:
   -- A Designer's Viewpoint
      Wendel R. Wendel, President
      Space Structures International Corporation

   -- A Builder's Viewpoint
      Allen Face
      Edward W. Face Company

2) Photogrammetry
      Clive Fraser
      Geodetic Services, Inc.

3) Macrometrology
      William Haight
      Director, Management Information Systems
      Martin Marietta

4) Automatic Vehicle Control in Site Preparation
      Boyd Paulson
      Stanford University

5) Materials Transport and Handling
      Kenneth Gans, President
      Gans & Pugh Associates

6) Automation in Construction
      Irving Oppenheim
      Carnegie-Mellon University

10:30 am	Coffee Break
11:00 am	Session One (continued)
12:30 pm	Lunch

DAY 1, AFTERNOON

1:30 pm	Session Two: Small Group Discussions List priority research issues for: 1) Grading, Ditching, Excavating, and Tunneling 2) Inventory Control and Material Handling 3) Framing, Assembly, and Finishing 4) As-Built Data Bases
3:00 pm	Coffee Break
3:30 pm	Session Two (continued)
4:30 pm	Second Round Delphi Forecast
5:00 pm	Adjournment
5:30 pm	Reception

DAY 2, MORNING

8:30 am	Session Three: Group Leader Panel/Open Forum
10:00 am	Coffee Break
10:30 am	Session Three (continued)
12:00 noon	Lunch

DAY 2, AFTERNOON

1:00 pm	Third Round Delphi Forecast
1:30 pm	Summary and Conclusion
3:00 pm	Adjournment

SECTION II

ABSTRACTS OF PREPARED PAPERS

AUTOMATION IN CONSTRUCTION: A DESIGNER'S VIEWPOINT

Wendel R. Wendel
Space Structures International
Plainview, New York

SPACEFRAMES--definition of a new building tool

TECHNOLOGICAL PALETTE

* New building systems:

  OCTA*HUB
  ORBA*HUB
  STAR*NET

* SSCAD

  Space Structures Computer Aided Design

SSCAD--Shared resource management in a complete system:

* Design Process
* Engineering Process
* Fabrication Process
* Assembly Process

DESIGN PROCESS--new forms and shapes possible with computers

ENGINEERING PROCESS--analysis and graphic information

FABRICATION PROCESS--computer integrated manufacturing (CIM)

* Shop drawings on SSCAD
* Computers used in shops
* Computerized numerical control fabrication

ASSEMBLY PROCESS--

* Assembly drawings
* Assembly planning
* Shipping planning

THE FUTURE--STAR*NET SYSTEMS and the "jobsite in the sky"

* Space City

ANALYTICAL PHOTOGRAMMETRY: A PRECISE THREE-DIMENSIONAL MEASURING TOOL FOR INDUSTRY

Dr. Clive S. Fraser
Geodetic Services, Inc.

Photogrammetry can be defined as the science and technology of obtaining reliable information about physical objects and the environment through processes of recording and measuring photographic images. Photogrammetric sensing and measuring systems have long been used for routine topographic mapping, but in the industrial environment, high-precision analytical photogrammetry has only enjoyed wide application as a three-dimensional measuring tool for the past five years or so. Nowadays, photogrammetry is routinely employed on mensuration tasks as diverse as providing control databases to guide robotic cutting and welding tools, and measurement of structures in Earth orbit.

As a non-contact measurement technique, photogrammetry can yield extremely high precision; with appropriate systems accuracies surpassing 1 part in 200,000 of the object size can be measured. In this presentation, the basic concepts of analytical industrial photogrammetry are reviewed and practical aspects of the technology are highlighted through reference to some of the numerous and varied mensuration tasks which Geodetic Services, Inc. has carried out over the past few years. The emphasis of the presentation will be placed on demonstrating the flexibility, accuracy, reliability and economy of industrial photogrammetry, as well as discussing the progress made in automating this measurement technique.

MACROMETROLOGY AT THE NATIONAL BUREAU OF STANDARDS

William C. Haight
Martin Marietta Aerospace

Macrometrology is the field of measurement science dealing with precision measurement of large structures, where linear dimensions typically exceed 10 meters and accuracy requirements approach and occasionally exceed 1 part in 100,000. This talk presents an overview of NBS activities in macrometrology, from the mid 1970's to the present time. Emphasis will be placed on measurement techniques and instruments, and four specific applications will be highlighted to illustrate the general utility of these tools. The applications are:

1. Volume of prismatic Liquid Natural Gas (LNG) tanks

    a. 125,000 m3 capacity supertankers for LNG import to U.S.
    b. Mathematical model for measurement procedure
    c. Flatness measurements - laser level
    d. Overall dimensions - theodolite & steel tapes
    e. Error analysis

2. Deformation of LNG tanks

    a. Deformation caused by lifting tanks into the ship and by hydrostatic loading
    b. Flatness measurements - laser level

3. Volume of Spherical LNG tanks

    a. Measurement of 37 meter diameter spheres
    b. Theodolite-based stero trangulation system developed, computerized data acquisition
    c. Target definition with laser target projector
    d. On-line error checking and coordinate determination

4. Positioning Accuracy of Industrial Robots

    a. Industrial robots must dimensionally coordinate motion with other objects in the work volume. How can their accuracy be assessed and improved?
    b. Theodolite-based stereo trangulation
    c. Ball targets on robot end effector
    d. Standard meter bar for metric definition
    e. Measurement accuracy +/- 0.025 mm (+/- 0.001 inch) for mid-size robots

AUTOMATED CONTROL AND DATA ACQUISITION FOR CONSTRUCTION EQUIPMENT

Boyd C. Paulson, Jr.
Stanford University

There are three main areas of application of automated control and data acquisition on a construction site. These are automated real-time data acquisition, operations analysis, planning and design, and automated real-time process control and robotics. This presentation covers these topics and highlights barriers to innovation in construction, ways to overcome those barriers and topics for research and development.

In automated data acquisition, opportunities include monitoring engineering parameters during construction, quality control, monitoring production rates and quantities including resource consumption and productivity, material tracking and control, short interval planning, operations analysis, and collecting input parameters needed for planning and monitoring automated real-time process control and robotics for field operations.

In real time process control and robotics, opportunities include automated process control of fixed plants, including concrete, aggregates, rebar cutting and bending, pipe spool fabrication, carpentry shops, and precast concrete element fabrication; partial or full automation of mobile construction equipment, including trucks, excavation and grading equipment, materials handling equipment and specialty equipment; spatially constrained manipulators for bolting, welding, painting, fireproofing, wiring, masonry construction and tunnel liner erection; and mobile robots, particularly for applications in hazardous environments.

Obstacles to applying technology in construction include unique projects, frequent reconfiguration of operations, an inadequately trained workforce with high turnover, severe environmental factors, social and economic factors, an industry structure that resists change, lack of interest of technology manufacturers and researchers, and a low priority that the construction industry places on technology.

Despite these obstacles, there is potential for applying new technology in construction. Applications in Japan are used to highlight this potential.

MOTOROLA'S POSITION SYSTEM PRODUCTS FOR AUTOMATING MATERIAL HANDLING

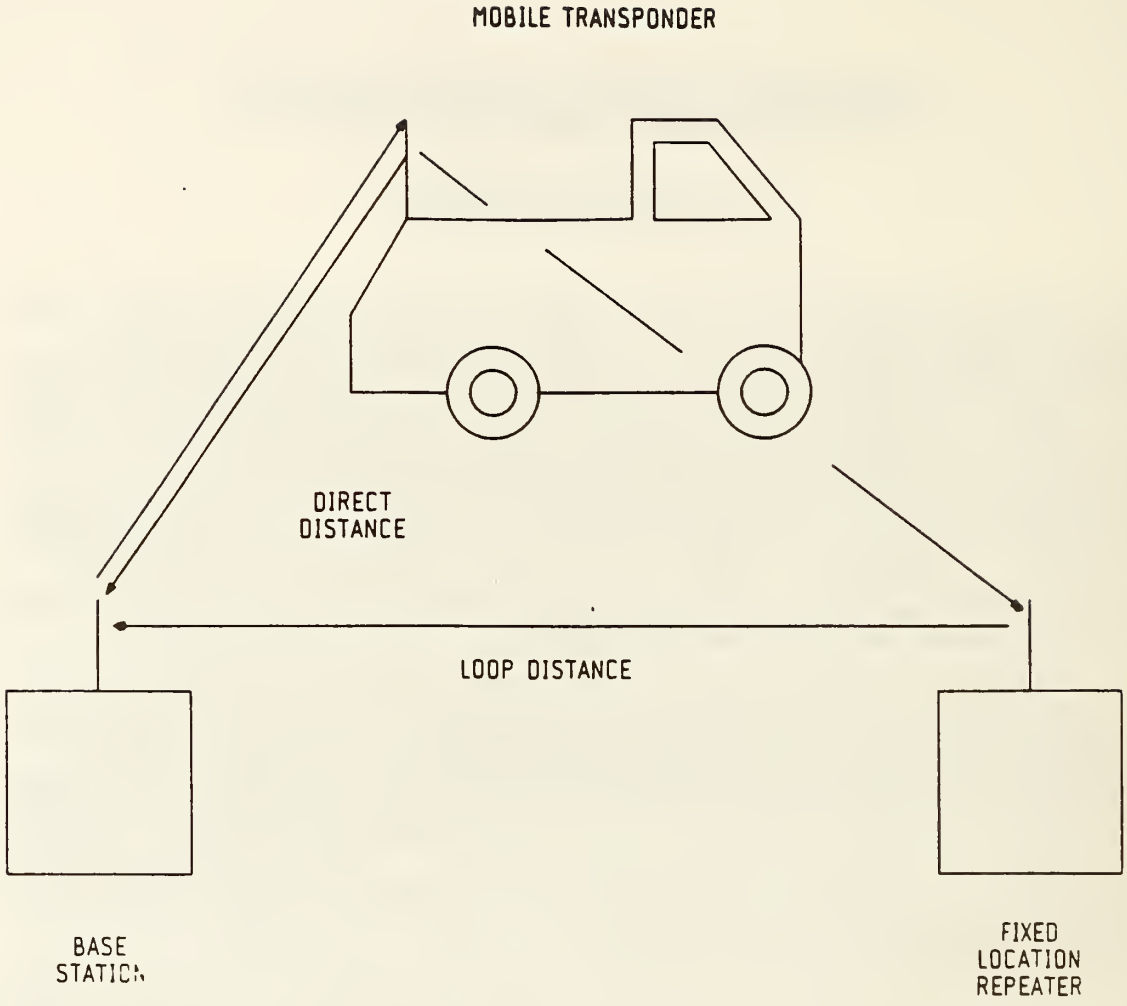
Kenneth Gans
Gans & Pugh Associates

For the past ten years Motorola has been offering radar based positioning systems products used primarily for navigation in the dredging and offshore oil rig positioning business. This product line, known as the Mini-Ranger, has been an outgrowth of military radar transponders. These products are used all over the world for real time positioning. The major limitation of this line is the fact that the range is limited to line of site, i.e., typically fifteen kilometers, and that active transponders must be used. The benefits are real time positioning with accuracies in the three to five meter range.

During the past year, Motorola has been working very closely with one of the major container ports in Europe to determine haw a tracking/position system could be incorporated into their port operations. Competition among container ports is keen, especially where a number of them are in close proximity to each other. The port that detains the ship, train or truck the least length of time represents the least cost choice for the carrier. Therefore efficient port operation is essential.

Motorola has installed a Falcon radar positioning system that tracks the position of the equipment that handles the containers in the port. This system is used to track the position of a container when it is picked up or stored and includes a two way data link from the mover to the master site.

In eight months of operation, Motorola has proven the system and has demonstrated a postioning accuracy of 1.5 meters in width of the container and 2.5 meters in length. This is sufficient accuracy for inventory management and meets the container port's requirements. Key features include easy installation, flexibility, unrestricted routing, multiple movers, and all weather operation.



MOTOROLA TRANSPONDER SYSTEM

CONSTRUCTION ROBOTICS: MEASUREMENT TECHNOLOGY AND RELATED ISSUES

Irving J. Oppenheim
Carnegie Mellon University

Intelligent robots for construction applications will rely on sensor, interpretation and data-management systems more advanced than those generally available for factory robotics. Every advance in sensor technology can be expected to generate new and additional applications. However, interpretation of sensor data must develop equally, as must data-structure capabilities, if full advantage is to be taken of such advances.

Five examples of measurement technology are discussed, each of them pertaining to present research at Carnegie-Mellon University with direct or potential ties to construction robotics. Contact sensing is used (with other sensing and intelligence) in a welding robotics effort. Magnetic vision consists of robotic sampling with a conventional magnetometer followed by advanced procedures for data reduction; the device is an improved system for detection of reinforcing bars within concrete, and has numerous other potential uses. Subsurface sensing is a related technology under development for mapping utility lines for a remote excavator. Sonar sensing is used to map solid room surfaces, and is also used for consequent navigation within building spaces. Vision is used in an autonomous vehicle research project, that vehicle also being a test-bed for construction robotics research. Note that these are cited only as examples, not as a comprehensive survey.

One immediate data structure requirement is three-dimensional modeling needed for navigation, obstacle avoidance, and general representation of a robot interacting with other robots and with work objects, all within some complex workspace. There is also great need for an integrated database system if full advantage is to be extracted from CAD, robot construction, and subsequent project operation, robotic maintenance, to eventual robotic demolition.

SECTION III

SMALL GROUP DISCUSSION RESULTS

The goal of the small group discussions was to develop priority research issues for:

1. Grading, ditching, excavating and tunnelling
2. Inventory control and material handling
3. Framing, assembly and finishing
4. As-built data bases.

On the second day, the leaders of each of the four small groups summarized the results of their group's discussions.

The results of the four small group sessions follow.

SUMMARY RESULTS

SMALL GROUP #1

Chairman: Jim Hill, Center for Building Technology,
National Bureau of Standards

Jack Richter, Kern Instruments, Inc.

Clive Fraser, Geodetic Services, Inc.

Boyd Paulson, Stanford University

Harry McCain, National Bureau of Standards

Fenton Harrison, NASA Langley Research Center

Hank Tobin, IIT Research Institute

Gif Albright, National Science Foundation

John Eberhard, National Academy of Sciences

Irving Oppenheim, Carnegie Mellon University

Wally Abel, Consultant

Len Haynes, National Bureau of Standards

GENERAL COMMENTS

Automation should be applied to do things that couldn't be done before, such as

- working in the dark,
- working in inclement weather, and
- working at remote sites.

It must be recognized that there are many different "construction industries", such as large excavating, industrial building, commercial building, housing, and rehabilitation. Each has its own set of unique problems.

The sensor technology needed for automation is, for the most part, already available. What is needed is considerable "system" or "integration" research.

Because of fragmentation within the industry, it will be necessary for government, industry and universities to work together cooperatively. Using NSF Engineering Research Centers would be one possible way to obtain cooperation.

A valuable product of this workshop would be a compilation of references for the construction industry on available sensor technology and measurement techniques. The National Bureau of Standards might undertake this task.

TUNNELING AND SITE WORK

There was considerable activity in the 1960's in tunneling. Since then, the market has decreased significantly, from 15 companies down to 5. The Japanese market is ten times the U.S. market.

Measurement technology is required in tunneling to "sense" ahead of boring; acoustic techniques are well developed.

Site work is the least expensive part of construction except in roads and civil works. This limits the potential for automation. In grading, the group recommended expanding the laser level technology to multi-dimensions and exploring the laser interferometer technique in use at NBS and the "Oculus" system available in Switzerland.

INVENTORY CONTROL AND MATERIALS HANDLING

Between 80 and 90% of construction labor cost is for materials handling; this represents a large potential impact in reducing construction costs.

Some new technology is already in use: microcomputers are incorporated on cranes for safety and Bechtel has implemented a system for location of materials on site.

Robot vision technology will not work since it is too difficult to recognize piles of material in an unstructured environment. One possible solution is to create an ordered structure of the environment plus the use of a combination of sensors (as in the Army munition loading project at NBS).

FRAMING, ASSEMBLY AND FINISHING

Assembly is just now being automated in the factory; it will be a late application for construction. Automation in this area will occur in institutional and commercial construction, not in housing.

If used, automated assembly could cause the largest innovation in the way construction occurs. For example, Russia created a new town for 250,000 overnight by producing components requiring minimum assembly effort.

Likely applications of automation will be spraying, painting, clamping, and pumping concrete.

Triangulation measurement technology is available and currently being used in automobile and aircraft factories. For construction applications, it will be necessary to develop proximity sensors and real-time photogrammetry linked to a CAD data base.

Control of vehicle movement for construction can be accomplished using the Geodetic Positioning System (GPS satellite system) currently available; real-time positioning from satellites to within 1 meter will be possible. GM is proposing to install GPS in cars by 1988. Inertial navigation systems are available but they are expensive and not suited for real time control.

AS-BUILT DATA BASES

Development of as-built data bases will be driven by clients, such as the Army, Navy, Bechtel, etc.

Widespread use of as-built data bases will not occur in this century.

There is a current Building Research Board project to develop prototypes of as-built data bases.

Standards are likely to be developed here before they will be developed in other parts of construction automation. Graphics, data dictionaries, and operating systems are areas requiring standardization.

SUMMARY RESULTS

SMALL GROUP #2

Chairman: Dennis Swyt, Center for Manufacturing Engineering, National Bureau of Standards

Bob Finkelstein, MITRE Corporation

John Stull, Bechtel Construction, Inc.

Ken Goodwin, National Bureau of Standards

Dan Halpin, Georgia Institute of Technology

Gene Leach, Caterpillar Tractor Company

James Acton, Todd Shipyards Corp.

Clayton Teague, National Bureau of Standards

GROUP #2 DISCUSSION RESULTS

Group #2 developed the following rank-ordered list of research topics.

1. SENSORS FOR AUTOMATIC CONTROL OF MACHINES

The identified need is for metrological sensors in feedback control systems to remove the operator from control of the construction processes.

Examples included grader blade height automatically controlled while the operator steers the grader. In the long-term future, earth movers and material handling equipment will have automatically-controlled loading.

2. SENSORS FOR AUTOMATIC ON-SITE METROLOGY

Four types of systems are needed:

- o To measure the dimensions of components for fit and compatibility.
- o To establish reference coordinates, e.g., elevation and position on-site and within structures.
- o To detect the presence of and give the coordinates of structures as built.
- o To feed as-built data bases for just-in-time, to-fit fabrication.

3. UPC LABELING OF COMPONENTS

Two standardization issues were identified:

- o Standard "Universal Product Code" labeling of fabricated parts for inventory and assembly control.
- o Identification of parts, etc., which can be standardized for interchangeability.

It should be noted that bar code labeling can be used for material tracking and inventory control on a job site with any numbering scheme. Industry wide standardization of labeling of purchased components is not required for part labeling to be useful.

4. STANDARDS FOR AS-BUILT DATA BASES

Standards or common practices are needed for documenting and saving the as-built characteristics of construction.

As-built drawings are now kept for nuclear power plants. Digital "drawings" of commercial or residential structures, as-built, would facilitate repair, rehabilitation, and nearby new construction.

5. MENU DESIGN OF STRUCTURES

CAD type data bases with "standard" modules and a link to CIM for custom design and manufacture of modular structures to customer preference would enhance productivity in both residential and commercial construction.

SUMMARY RESULTS

SMALL GROUP #3

Chairman: Jim Albus, Center for Manufacturing Engineering, National Bureau of Standards

Don Michael, Wild Heerbrugg Instruments, Inc.

Chuck Shaeffer, Wild Heerbrugg Instruments, Inc.

Robert Gold, Office of Technology Assessment

Joseph Engelberger, Transitions Research Corp.

Wendel Wendel, Space Structures International

Demos Kyrazis, R & D Associates

Allen Face, Edward W. Face Company

Tim Pryor, Diffracto, Ltd.

GROUP #3 SUMMARY

1. ON-SITE METROLOGY

The problem of on-site metrology falls into several categories depending on the accuracy and resolution requirements, and type of coordinate frame.

There are measurements for establishing a metric over the entire site so that the position of objects such as sewer pipes, foundations, roads, street lights, etc., can be measured relative to a global site coordinate system fixed by benchmarks established by the site survey.

There are also measurements needed to establish a metric within a local coordinate system such as a room, or the floor of a building, so that objects such as electrical outlets or plumbing fixtures in a room or air conditioning ducts on a floor can be installed.

Several categories of accuracies and resolutions are required. For example, for inventory control of pallets of materials laid out by a forklift, accuracy of a meter or so is quite adequate. For control of a bulldozer for grading a road, accuracy of a few inches is adequate. For control of steel framework for buildings, a few tenths of an inch is required. For installation of windows, doors, trim, etc., a few hundredths of an inch is desirable.

Sensors for relative measurements of gaps and spacing need one type of resolution, sensors for positioning objects relative to a coordinate frame of reference need another type of resolution.

Measurements of positioning relative to a coordinate frame are typically performed using some type of theodolite for measuring angles, plus in some cases a method for measuring distance such as a tape, laser range or RF transponder.

High quality theodolites can measure to about 1 part in 600,000. This translates to 1 millimeter at 600 meters. However, thermal errors and unfavorable sighting angles may reduce this to less than 1 millimeter in 100 meters.

Typical systems are manually pointed, although some advanced systems are electrically interfaced to computers so that readings can be automatically recorded. Automatic tracking systems that can automatically follow a cooperative target are under development.

A variety of devices for pointing laser beams and for measuring distance along the beam already exist, and others are under development. Under ideal conditions, current commercial time-of-flight systems can achieve an accuracy of between 2 and .2 millimeters. These systems typically require a corner cube retroreflector to be mounted on the device being measured. Systems under development promise to have accuracies of .01 millimeter, and for distance of less than 10 meters, these systems will be able to operate without special reflector devices.

Methods of pointing laser beams typically depend on mirrors positioned by galvanometers or stepper motors. Automatic pointing accuracies on the order of a micro-radian have been demonstrated in the laboratory.

There are a number of different ways that triangulation and/or distance measuring devices can be used to establish a metric on a construction site. The choice depends on specific applications and requirements.

RF transponders typically have a resolution of about one meter. This is inadequate for building dimensions, but can be used in conjunction with local collision-avoidance sensors for navigation of automatic vehicles such as forklifts. Navigation satellites such as NAVSTAR can provide similar accuracies, but these systems tend to be extremely expensive.

2. INVENTORY CONTROL AND MATERIAL HANDLING

A number of opportunities exist in this area for productivity increases based on advanced technology. Some things are feasible right now with current technology, such as automatic navigation of forklift trucks and automatic inventory control systems that can turn materials storage lots into the equivalent of automatic warehouses with computer controlled storage and retrieval systems. Other things will require several major technological developments before they can be accomplished, such as artificial intelligence for construction site supervision. The following list of potential application areas for advanced automation were discussed:

a) Real-Time Project Scheduling
Schedules and PERT charts are often developed by computer programs for an entire construction job, and may be periodically updated as the job progresses. However, such schedules are not updated on a daily or hourly basis to take into account changing conditions on the site, except by a human on the job. Real-time scheduling of material deliveries so that parts arrive just in time to be installed

is beyond the state-of-the-arts, even in manufacturing environments where the job is much more structured and less subject to unanticipated conditions. It will be many years, probably decades, before automatic real-time project scheduling can be done automatically on the construction site.

b) Just-in-Time Delivery
Large savings would occur in inventory and storage costs, as well as in prevention of damage to materials and theft, if it were possible to schedule deliveries just in time for use. However, this cannot be achieved before the real-time scheduling problem cited above is solved.

c) Communications Network to Suppliers
Once "as-built databases" exist, communications to suppliers could allow parts to be cut to fit, perhaps automatically, and delivered to the construction site just hours before they were to be installed. All parts could be labeled and coded to the drawings so that there would be no need to measure and cut on the site, only to fasten.

d) Real-Time Redesign
Proper measurement technology on site would enable computer readable, as-built databases to be established. These could be made compatible with the as-designed database, and a designer could make on-line design changes with all the effects of those changes being checked by an expert system. The new dimensions would be reflected immediately in the automatic cut-to-fit machinery, and all parts delivered would be guaranteed to fit. The effect would be that design changes could be made with minimum cost.

e) Artificial Intelligence (AI) for Site Supervision
There are a number of potential applications of artificial intelligence on the construction site in addition to those mentioned above. For example, expert systems could examine equipment access, or check for conflicts between subcontractor activities.

3. FRAMING, ASSEMBLY, FINISHING

In order to automate these activities, there needs to be significant effort in design for automatic assembly. Design drawings need to specify precisely how wires, pipes, and ducts are to be cut and routed. As-built databases are needed so that parts and materials can be cut to the exact sizes required. But beyond this, parts need to be designed

so that assembly operations are enormously simplified. For example, current practices often require large pieces of pipe, duct, and conduit to be manuevered through tight spaces without collisions. Often, parts that need to be joined are flexible and require force and tactile sensing in order to mate. Because of the difficulties inherent in these type of operations, assembly and finishing will require significant human interaction for a very long time.

Structure --
Assembly of the structural components of a building is perhaps the easiest to automate, because there are the fewest constraints. Parts can be cut to the design specifications, put in place and fastened. Spatial clearance is typically not a problem, since pieces are added from the bottom up and from the inside out.

Electrical --
Wiring conduits, outlets and switches need to be redesigned for automatic installation. Wall, floor, and ceilings also need to be designed so that electrical fixtures can be easily installed.

Ventilation and heating --
Duct work will be particularly difficult to automate because of the large bulky flexible sections which must be fitted together. Precise information from an as-built database would make it possible to precut duct sections to the exact sizes required, but the positioning and assembly tasks will present formidable problems for automated systems.

Plumbing --
As-built database information would also permit pipe to be cut and bent to the precise size and shape for installation. Automatic joining equipment could facilitate the installation process, but totally automatic installation of plumbing is well in the future.

Global navigation --
The problem of a machine automatically finding its way around a construction site can probably best be solved by beacons or transponders which give position and heading relative to known points fixed on the site. Dead reckoning can be used between beacon sightings.

Local navigation --
The problem of a machine automatically avoiding obstacles and navigating relative to objects in the environment can best be solved by proximity sensors using acoustic sonar, visual or touch sensing devices.

It seems unlikely that completely automatic control of large construction machinery will be practical in the near future for a number of reasons, not the least of which are reliability and safety. However, semiautomatic control may be useful in several applications. For example, systems which use a laser beam to control the height of a bulldozer blade while a human drives and steers the machine are routinely used for grading farmland for irrigation in California. In the future, lifting/positioning systems could be developed for supervisory control by a human operator, but with automatic terminal guidance for precise insertion of loads into tight spaces.

5. AS-BUILT DATABASES

Buildings are never constructed exactly as designed. At best, there are slight variations between the architectural design and the finished product. Often, these differences are significant. The as-built database documents these differences for future reference. If kept current, the as-built data can provide the information needed to cut parts to fit the existing structure.

The development of as-built database technology is critical to the efficient introduction of automation into the construction site. It is essential to an automatic system to know exactly where things are and how large the spaces are into which parts must fit.

The first step in constructing an as-built database would be to design the structure with built-in control points. The precise measurement of these control points would provide reference coordinates for as-built data. Additional measurements, for example inside rooms, could be made against these control points.

Theodolites and photogrammetric instrumentation with automatic data entry to an on-site computer system would be desirable for collecting the required as-built data. Portable targets which could be automatically or manually tracked might assist in the data collection function. Advanced systems might use automatic scene analysis techniques to find and measure critical features such as edges and corners.

Real-time, on-site metrology would make the as-built database sufficiently current so that it could be used to control machinery to cut parts to fit for just-in-time delivery. In a highly automated site, measurement equipment used to collect as-built data might be similar to or even the same as that used for controlling machinery.

If the as-built database were stored in a standard format, it could be made available to subcontractors, possibly even in real-time through an on-line communication system. This would allow subcontractors to deliver custom cut parts just-in-time for assembly.

SUMMARY RESULTS

SMALL GROUP #4

Chairman: John Evans, Transitions Research Corporation

David Hattis, Building Technology, Inc.

Ed Kuipers, University of Wisconsin

Ken Waldron, Ohio State University

Ernest Glauberson, NAVSEA

Al Bradford, NAVFAC

Ken Reinschmidt, Stone & Webster

Greg Baecher, MIT

Don Washburn, R & D Associates

Bob Beiner, Masonry Institute

GENERAL COMMENTS

Group #4 distinguished two different needs for sensing on a construction site:

- To feed an as-built data base, and
- For real-time closed loop control.

Data bases may involve both geometric and non-geometric data and may have to be maintained at several levels of resolution for different uses. For example, the resolution needed to locate an object for maintenance is less than the resolution needed to generate a drawing to fabricate a replacement part.

Data bases including as-built data will have value that increases in time. However, the costs of creating the data base are incurred immediately. Hence, the issues are who owns the data base, who maintains it, and who pays for it.

The group pointed out that new materials and designs will change the industry and that you don't want to automate obsolete concepts. On the other hand, new concepts may enable automation which would not otherwise be possible.

GRADING, EXCAVATING, DITCHING

The following measurement needs were identified:

- Measurements of site and materials properties, including soil compaction and concrete composition.
- Measurements for vehicle control, including vehicle location, grader blade height, trench depth, etc.
- "Awareness" of the environment of an automatic machine for collision avoidance and navigation.
- Measurements for retrofit and infrastructure work, including pavement, gas and water lines, and other underground services. It was noted that working on utilities in urban intersections involved almost an archeological excavation. Magnetometers can detect steel pipes, but plastic pipes and fiber optic communication lines will be very difficult to detect.

INVENTORY CONTROL AND MATERIAL HANDLING

The location and identification of inventory involve two issues:

- o Tracking vehicle location when moving inventory, and
- o Labeling items with bar codes or "smart" tags for inventory tracking and management.

The use of cranes for material handling drew a great deal of discussion. Cranes are as close to robots as anything on a construction site today. Applying concepts developed for robot control systems could improve the performance of cranes. Examples of possible improvements include:

- o Calculating optimal trajectories with no overshoot,
- o Coordinate transformations to allow the operator to guide the load with respect to the workplace rather than in the polar coordinate system of the crane,
- o Obstacle avoidance and avoidance of collisions with other cranes and equipment,
- o Improved sensing to avoid overloads and overturns,
- o Compensation for wind sway,
- o Cooperative work between two or more cranes, and
- o Maintaining an audit trail for failure analysis and for preventive maintenance.

FRAMING, ASSEMBLY, AND FINISHING

The primary issues are quality control and speed. It was agreed that the greatest use of automation would be in fabrication and inspection of factory built components.

On site applications include automatic location of components, sensing of vertical for plumbing columns, and lining up pipe for welding.

As-built data bases for part fabrication and later maintenance should be created during assembly. Of particular importance are piping, duct work, and wiring, which is often discretionary.

SECTION IV

MERGING AND PRIORITIZING SMALL GROUP REPORTS

Based on the open discussion on each of the small group presentations, four areas of common interest were identified:

1. On-Site Metrology
2. Machine Control
3. Data Bases
4. Inventory Control and Project Scheduling

The results of the four groups were correlated against these topical areas, and a "straw-man" list of projects was assembled in each area. The barriers, approaches, priorities and R&D issues relating to these topics were discussed and prioritized by the workshop participants. The presentations and conclusions of these topical discussions follow.

ON-SITE METROLOGY

After reviewing the results of each of the small groups and prioritizing results, the following conclusions were reached as to a priority list of major issues for research in the area of on-site metrology for construction and large scale assembly:

1. Most Important

   Real-time position/distance measuring systems (i.e., position relative to a coordinate system).

2. Next Most Important (close second)

   Real-time dimensional measuring systems (object size)

Issues raised during discussion

1. In shipbuilding, special requirements exist for dimension measurement of large dimensions.

2. In locating the position of columns, pipelines, ducts and other components as-built, there may be special sensors or detectors needed to determine the presence and location of objects, e.g., buried pipelines.

3. In all dimensional and distance measurements, tolerances should be carried with the dimension in a database system. Tolerances should relate to the intended use of the dimensional data.

4. There is a need for an information resource on measurement technology. NBS could provide this resource.

MACHINE CONTROL

Types of construction machines discussed in the various groups included spraying, ditching, grading, materials handling, lifting, positioning, cut-off, bending, masonry, welding, concrete placement and finishing, fastening, and inspection machines.

Most concepts discussed were for semi-automated machines with a computer control system assisting the operator, as in Figure 1. A common concept was automatic process control with manual steering, as in the example of grading.

Issues involved in machine control include stability, accuracy, work volume, computer database interfaces, man-machine interfaces, speed, load capacity, sensors, data analysis, machine intelligence and general issues of cost-benefit analysis.

The workshop concluded that the priority areas for further research on machine control were:

1. Materials Handling
2. Lifting and Positioning
3. Inspection

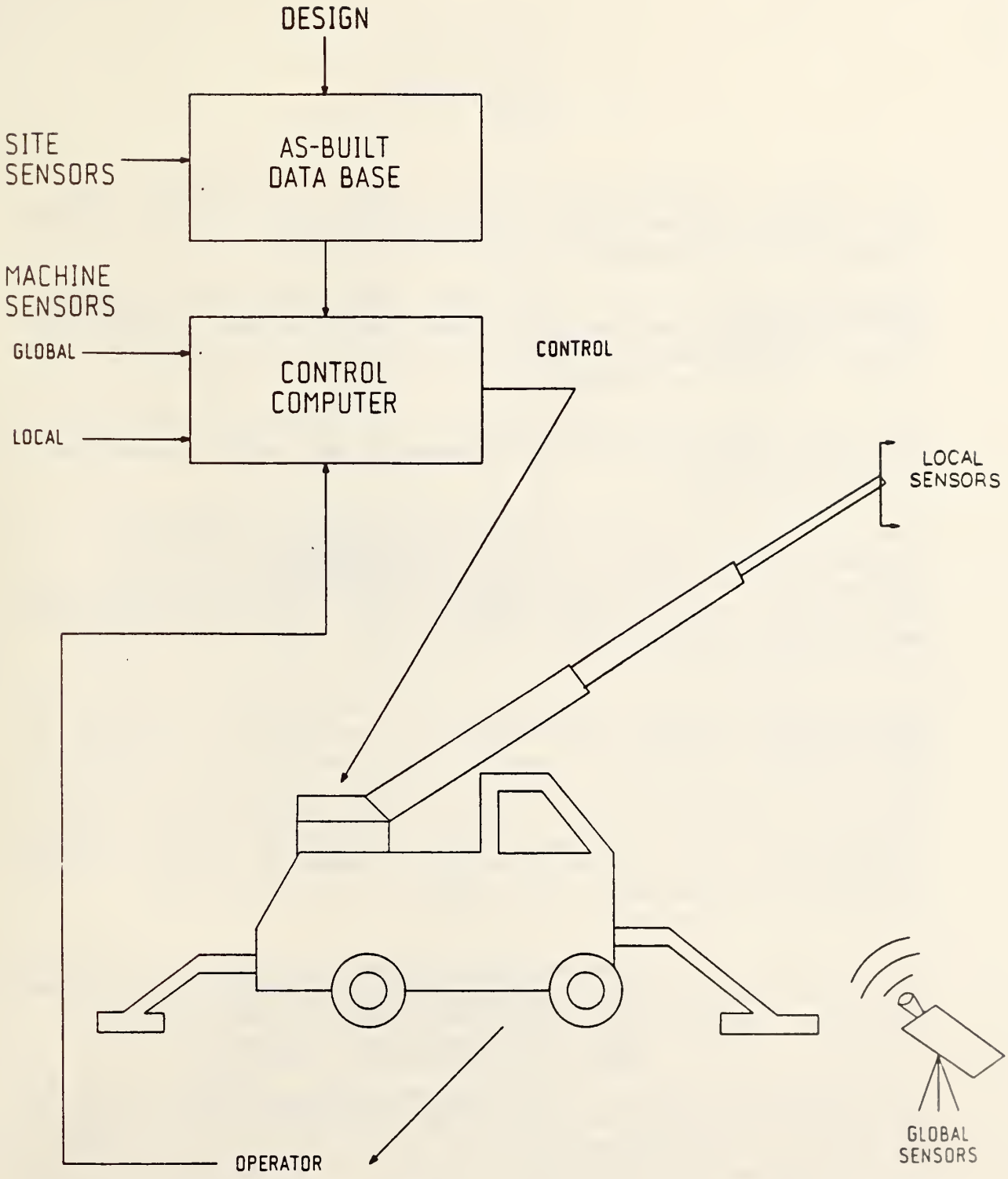


FIGURE 1
MACHINE CONTROL

DATA BASES

The workshop distinguished three types of data bases: CAD, as-building, and as-built. The major issues are in creating, managing and standardizing these data bases.

CAD data bases are very important. They are used in design and for engineering analysis, part fabrication, purchasing, project management, on-site control of site preparation, and on-site control of assembly.

The major issues in improving the utilization of CAD data are data interchange to on-site computers and data interchange to subcontractors.

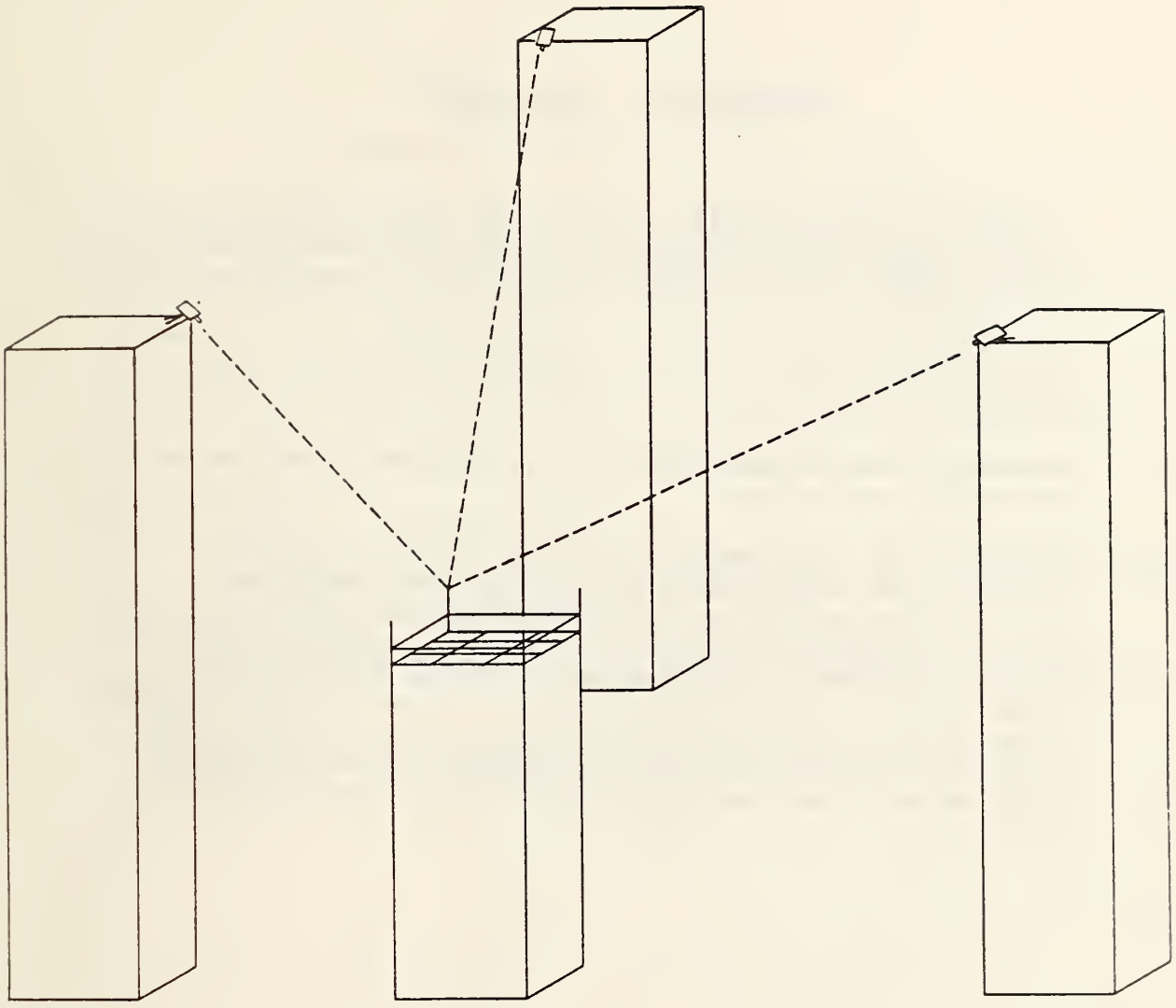
Barriers to better use of CAD data bases are industry fragmentation, a lack of application engineering and customizing services from vendors, problems in system integration and in associating graphic and non-graphic data, and the cost of initially running dual paper and computer systems in parallel.

As-Building/As-Built data bases are needed for on-site part fabrication,and more generally for facilities management, maintenance and repair, and for later nearby construction. Such data bases can be created by ties to on-site metrology systems, locating portable targets for theodolites, laser ranging systems or photogrammetry systems at control points determined by the building design. Although general scene analysis was discussed, this seems less useful than traditional mensuration techniques.

Site surveys after completion of construction could identify the location of pipes, cables, ducts and other discretionary placement components inside the structure, and highways, bridges, parking lots, and other outside features.

The Building Research Board of the National Academy of Sciences is working on this area. Standards will be needed. Barriers to implementation will be the issues of who pays for the creation of this data, who owns the data, and who is responsible for maintaining the data. Joint efforts of AEC firms and building owners may be needed.

A demonstration project to create an as-built data base and compare the as-built dimensions to the as-designed dimensions was recommended. A possible approach is shown in Figure 2.



MONITOR CONSTRUCTION PROJECT
COMPARE WITH DESIGN DATABASE
DOCUMENT TECHNOLOGY, SYSTEMS
INTEGRATION, RESULTS

FIGURE 2

SUGGESTED DEMONSTRATION PROJECT

CONCLUSIONS: DATA BASES

The priority issues recommend by the workshop are:

1. A demonstration project to create an as-built data base, documenting and disseminating the technology, system integration issues, and results for a real construction project.

2. Standardization of data elements for an as-built data base.

3. Research and standardization of issues involved in system integration.

4. Research on data base technology, particularly integration of graphic and non-graphic data and customizing existing technology to the needs of the construction industry; also the possibility of an expert system for automatic checking design for compliance with building codes. It was noted that this area offers a business opportunity for existing AEC firms or computer firms or some new firm to provide data base technology services to the construction industry.

INVENTORY MANAGEMENT

The general problems of inventory management include scheduling, locating and identifying material, access to the site for cranes and material handling equipment, and avoiding interference between subcontractors. The measurement related issues are material location and identification.

Potential solutions to identification include UPC bar codes, "smart" tags (active or passive coded transponders), and research on robot vision.

The workshop recommended that:

1. Labeling of material for location and identification should be investigated.

2. Use of UPC and "smart" tags for labeling should be investigated.

3. NBS should coordinate members of industry in undertaking these investigations.

FINAL DISCUSSION

Overall ranking of importance of the topics discussed:

1. Data Bases
2. Inventory Control and Material Handling (close second)
3. On-site Metrology
4. Machine Control

The next participants felt that another conference on this topic next year would be useful. Possible sponsors:

American Institute of Architects
Building Research Board (National Academy of Sciences)
Society of Civil Engineers
Construction Engineering Institute
Carnegie Mellon University
McGraw Hill
Building Owners & Operators Association
International Facilities Management Association

The need for information transfer was stressed.

SECTION V

DELPHI FORECAST

A Delphi Forecast was used to develop predictions as to the rate of diffusion of new technology in construction and large scale assembly and to rate the economic benefit of new technology over the next ten years.

A Delphi Forecast is done in three rounds to develop a consensus opinion. The results of the third and final round are included in this section.

The results for the first twelve questions were dates by which certain events would occur. The minimum, maximum and quartiles (25%, 50%, 75%) are shown for each question. The median (second quartile) is considered the consensus answer.

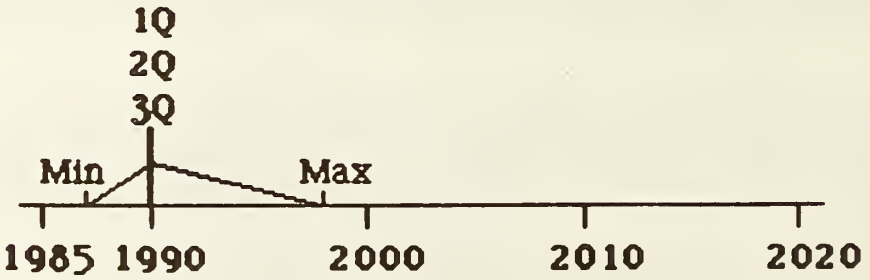
The results for the last nine questions were ranked (on a scale of 1 to 10) in terms of economic benefit from different new technologies over the next 10 years. Again, the minimum, maximum and quartiles are shown.

DELPHI FORECAST

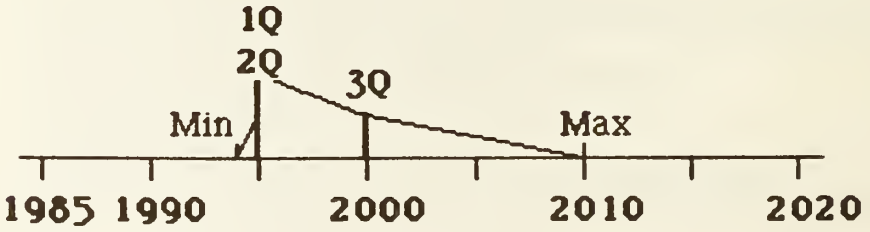
SITE PREPARATION

Semi-automated construction equipment with guidance sensors (such as bulldozers with automatically-controlled blade height using laser-level sensors) are already in use.

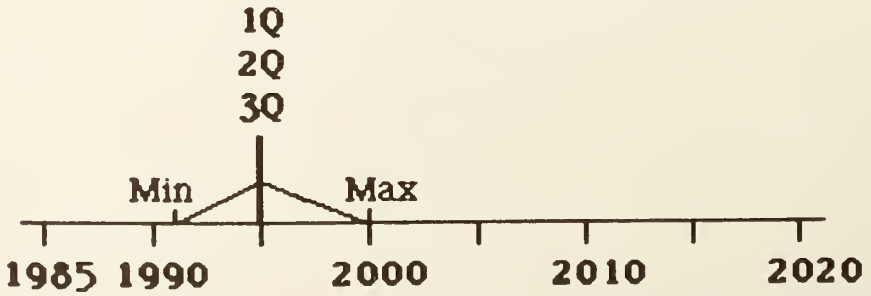
1. When will 5% of new construction equipment be equipped with such semi-automatic control?



2. When will 50% of new construction equipment be equipped with semi-automatic control?



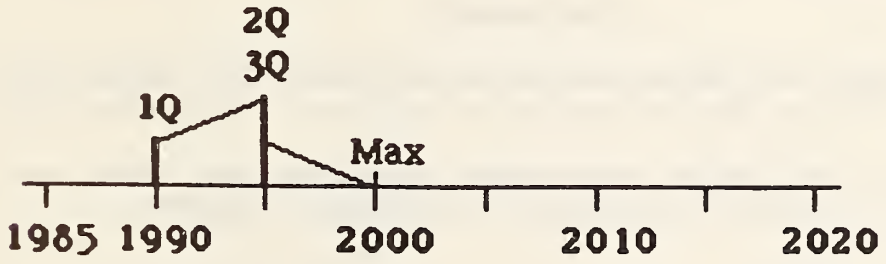
3. When will 5% of all construction jobs have digging, grading and ditching equipment controlled by data from a computer data base?



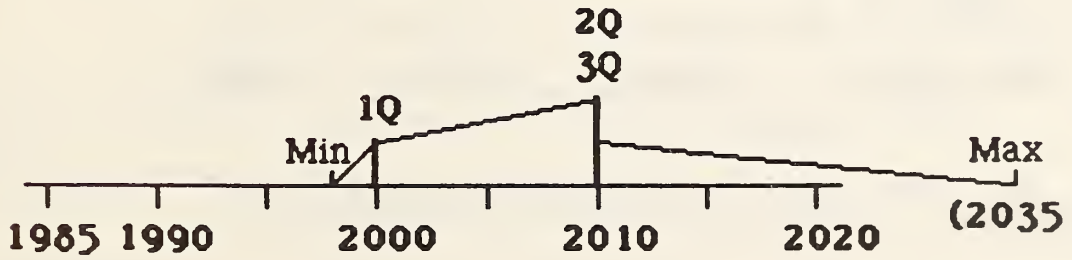
SITE MANAGEMENT AND CONSTRUCTION

In the future, position-measuring sensors (such as lasers, LED beacons, radio frequency ranging systems, radar, etc.) will allow automatic navigation of equipment for inventory tracking, and automatic control of equipment for material handling.

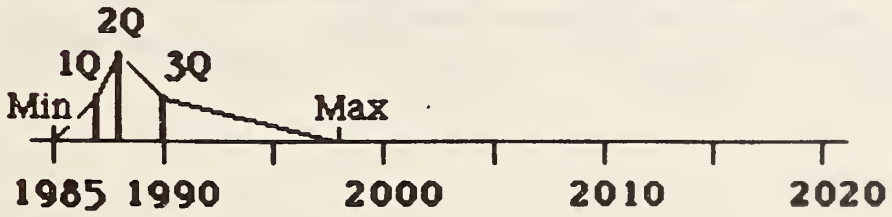
4. When will 5% of all commercial construction sites have such sensors and control systems?



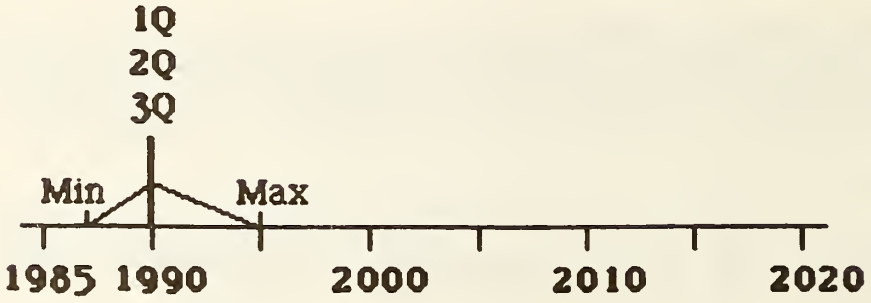
5. When will 5% of residential construction sites have such sensors and control systems?



6. When will 5% of aircraft assembly use such sensors and controls?



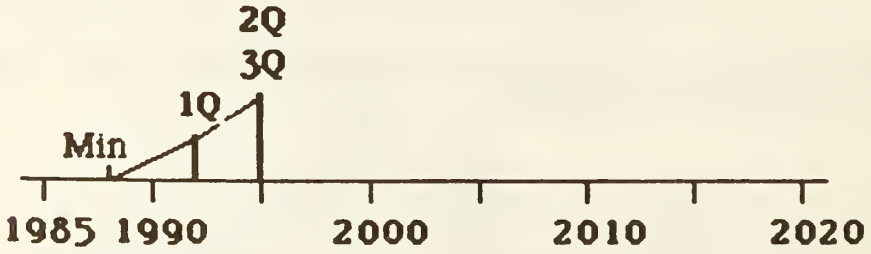
7. When will 5% of shipyards use such sensors and controls?



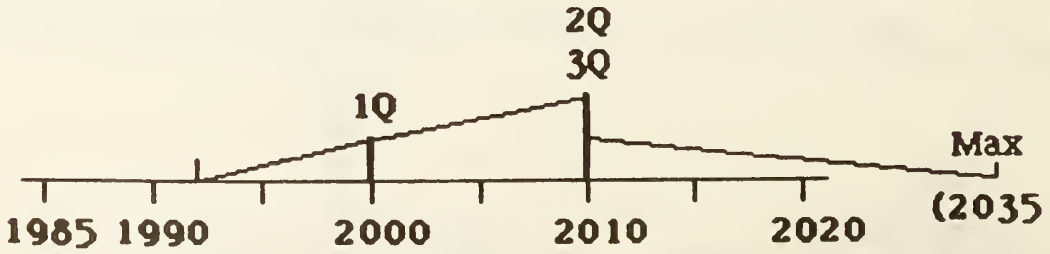
DATA BASES

Measurements are now made to document "as built" dimensions and details of some buildings (e.g. nuclear power plants).

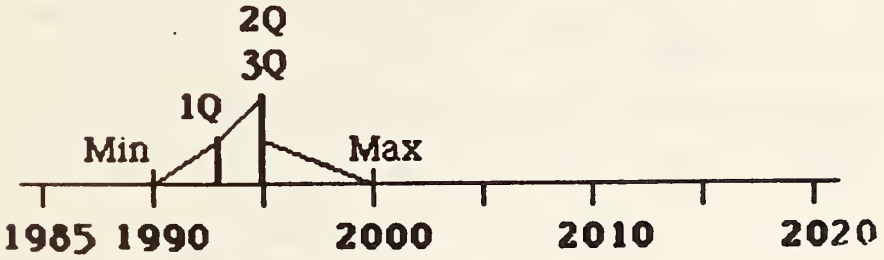
8. When will 5% of commercial construction sites use "as built" data bases for on-site part fabrication?



9. When will "as built" data bases be used for part fabrication in 5% of residential construction?

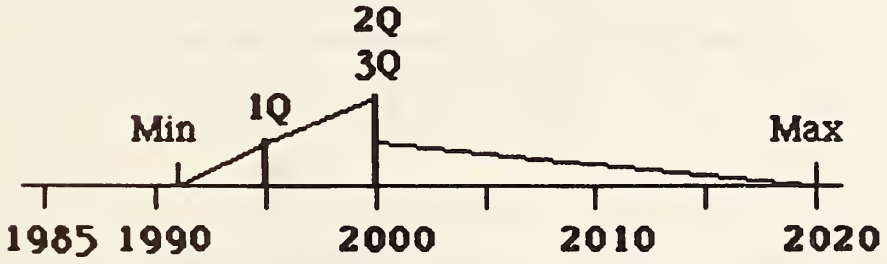


10. When will measurement sensors directly feeding a computer data base be used on 5% of all commercial construction sites?



STANDARDS

11. When can we expect standards for "as built" data bases?

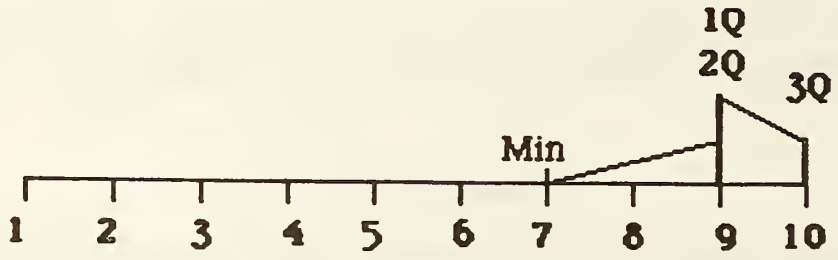


12. When can we expect standards for data transfer between CAD systems and on-site computer systems (IGES, PDDI)?

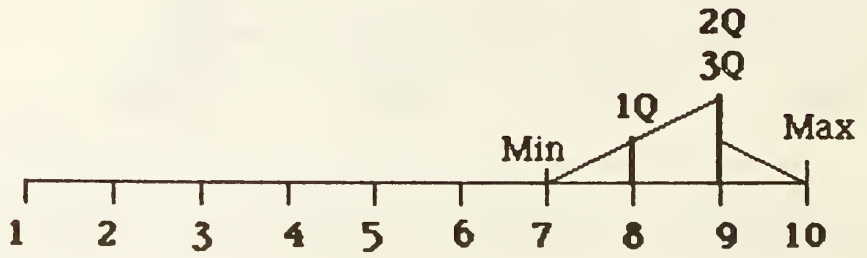
NEW TECHNOLOGIES

On a scale of 1 to 10, indicate how important you feel the following technologies will be for near term (ten year) economic benefit in the construction industry (1 = not important, 5 = some importance, 10 = extremely important throughout the industry).

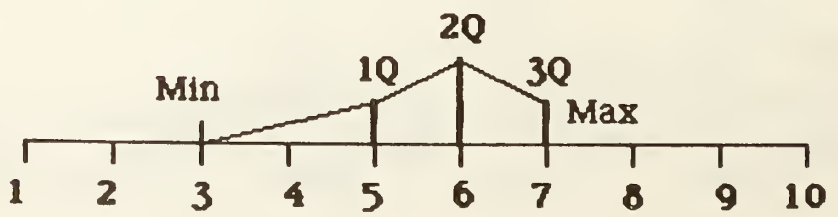
13. CAD systems for architectural design.



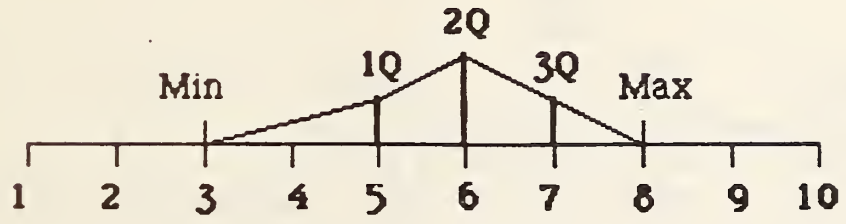
14. Computer-assisted surveying and measurement techniques.



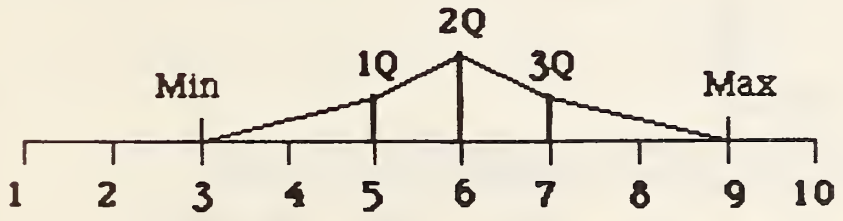
15. Semi-automated control of ditching and grading machinery.



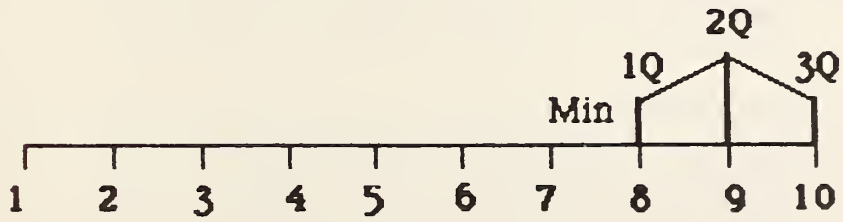
16. Semi-automated control of lifting and positioning devices for heavy loads.



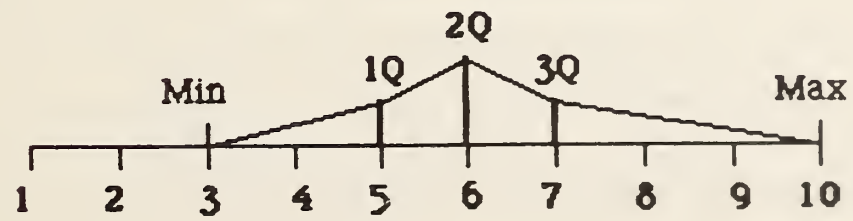
17. Semi-automatic control of materials handling machinery.



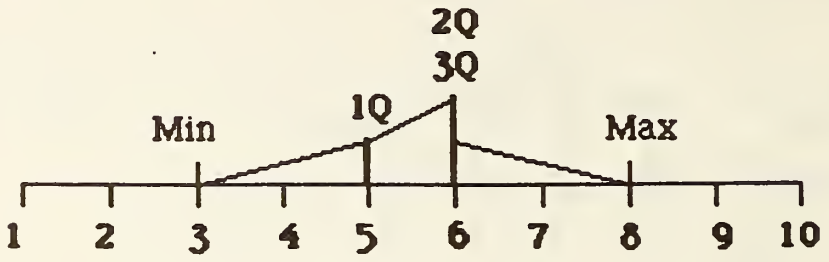
18. Computer-aided inventory control and scheduling of materials delivery.



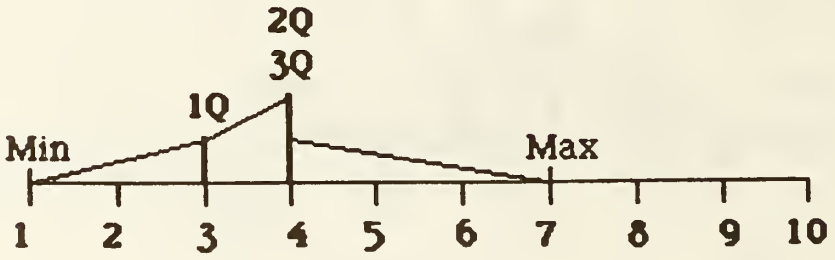
19. Computer-controlled cutoff equipment for boards, panels, and masonry.



20. Computer-controlled spraying equipment for painting, fireproofing, plaster, concrete, etc.



21. Computer-controlled machinery for laying brick, block, tile, etc.



SECTION VI: SUMMARY AND CONCLUSIONS

Relative Importance of Technologies

The most important aspect of measurement technology in construction is creating a structured way to use the data from the measurements. That is, the key to on-site metrology is not the instruments to take data but the creation and management of the as-built data base to organize and manage the data.

The workshop concluded that the necessary sensor technology was generally available. What is needed is considerable "system" or "integration" research.

The ranking of the subjects discussed at the workshop was:

1. Data Bases: particularly a demonstration project of an as-built data base and standardization of data elements and interfaces.

2. Inventory Management, particularly on-site part labeling and tracking of material handling equipment.

3. On-Site Metrology, to measure the as-built structure characteristics and to feed the as- built data base. Important measurements are position, dimension, and measurements for quality assurance.

4. Measurement for Automatic Machine Control, particularly semi-automatic machines in which the process control is automatic and the operator drives the machine and controls set points. Lifting (cranes) and material handling were considered most important.

Economic Benefit

The ranking of the economic benefit over the next ten years from new technology clearly split into three classes:

1. Very important (ranking of 9 on a scale of 10)

   -Computer Aided Design systems (9)
   -Computers for inventory control and material scheduling (9)
   -Computer assisted surveying and measurement techniques (9)

2. Important (ranking of 6 on a scale of 10)

-Semi-automated control of ditching and grading machinery (6)
-Semi-automated control of lifting and positioning machinery (6)
-Semi-automated control of materials handling machinery (6)
-Computer controlled cutoff equipment for boards, panels, and masonry (6)
-Computer controlled spraying equipment for painting, fireproofing, plaster, concrete, etc.(6)

3. Less Important (ranking of 4 on a scale of 10)

-Computer controlled machinery for laying brick, block, tile, etc. (4)

Delphi Forecast

The penetration of new technology was predicted to be fairly rapid. Specific forecasts:

1. By 1990:

-5% of new construction equipment will be equipped with semi-automatic control such as laser level control of grader blades.

-5% of aircraft assembly will use position sensing systems for navigation and control of material handling equipment.

-5% of all shipyards will use such sensors and control systems.

2. By 1995:

-50% of new construction equipment will be equipped with semi-automatic control.

-5% of all construction jobs will have digging, grading and ditching equipment controlled by data from a computer data base.

-5% of all commercial construction sites will have automatic position sensing systems for navigation and control of equipment.

-5% of commercial construction sites will use "as-built" data bases for on-site part fabrication

-5% of all commercial construction sites will have measurement sensors feeding directly into a computer data base.

-Standards will be developed for data transfer between CAD systems and on-site computer systems (such as IGES, PDDI).

3. By 2000:

-Standards will be developed for "as-built" data bases.

4. By 2010:

-5% of residential construction sites will have position sensor systems for equipment location and control.

-5% of residential construction sites will use "as-built" data bases for on-site part fabrication

Recommendations

In summary, the workshop reached a clear consensus that new technology would have a major benefit in construction in the near term future, and that the key was the application of computers both off-site for design and planning, and on-site for inventory management, project management, and the creation of an as-built data base.

Problems that need attacking are:

1. System integration and standardization of data base technology for on-site use, for integration with measurement and inventory management systems, and for integration with off-site computers.

2. Standardization of labeling for inventory management.

3. Development of real-time measurement technology for measuring position and dimensions and for inspection for quality assurance, particularly in materials properties (e.g. concrete).

4. Development of better machine control technology, particularly for lifting (cranes) and for material handling.

Specific recommendations for action included:

* Information Transfer: a source of information on measurement technology and a major conference on this topic next year.

* A Demonstration Project to develop and demonstrate an as-built data base on a real construction project.

APPENDIX

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Fifty technical experts from business, industry, universities and government met in Washington, D.C., on February 5 and 6, 1985, to consider the issues of applying automation to construction and large scale assembly. Thisworkshop, sponsored by the National Bureau of Standards and Transitions Research Corporation, concluded that:

- o New technology achievable in the near term would have a major benefit in the construction and large scale assembly industries.
- o The key to this benefit is the application of computers to data management and process control both off-site for design and planning and on-site for inventory management, production control and creation of an as-built data base.
- o The achievement of this new technology requires research carried out on the integration of systems for measurement and automated control of on-site construction and assembly tasks.

The consensus of the attendees at the workshop was that the specific problems that need attacking are:

1. System integration and standardization of data base technology

(See attached continuation sheet)

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

as-built data base; assembly; automation; construction; machine control;, metrology; robots

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for on-site use, for integration with measurement and inventory management systems, and integration with off-site computers.

2. Standardization of labeling for inventory management.

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4. Development of better machine control technology, particularly for lifting (cranes) and for meterial handling.

Specific recommendations for action included:

- Information transfer: a source of information on measurement technology that could be applied in construction and a major conference on this topic next year.

- A demonstration project to develop and demonstrate an as-built data base on a real construction project.